Detection and Characterization of Events with an OTDR

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Abstract—In this dissertation it was developed a detection and analysis algorithm of existing singularities in an optical fiber, characterized by an optical time-domain reflectometer. Thus, various signal processing techniques and singularities detection methods were studied in a first phase, whose goal was to find a solution which showcased the best results. Of the various methods tested, only two were introduced in the algorithm. The second phase of the study consisted in the implementation of an algorithm based on two event detection methods. The first method was the match filter which consists in the creation of a model and its correlation with the slope between signal samples obtained by the reflectometer, occurring an increase in the size of singularities present in the signal and facilitating their detection. The second method was based on the conventional Kalman filter implementation using a linear model of the reflectometer signal. The results showed that the proposed algorithm is able to detect and analyze existing singularities in the signal, quickly and with great precision. A subjective analysis function was created to evaluate the performance in terms of accuracy and detection capability in which the algorithm got a better score compared to tested commercial solutions.

Keywords—OTDR, Backscattering, Match Filter and Kalman Filter.

I. INTRODUCTION

The OTDR test equipment is able to measure the loss along the fiber due to Rayleigh backscattering, the loss due to joints and connectors and the optical return loss (ORL). This equipment is able to make these measurements from one end of the fiber without destroying it in the process. More advanced equipment’s also provide a report describing the status and location of each optical component and events.

The laser sends pulses of light that are directed through the optical coupler (or circulator) and then through the connector, into the fiber under test. Connectors, mechanical joints and unfinished fiber ends cause Fresnel reflections that return light back to the OTDR [1]. When the light reaches the OTDR, the coupler directs it to the optical receptor. This receptor is typically an avalanche photodiode (APD). The purpose of the optical receiver is to convert the optical power into electrical current that is then amplified, sampled, digitized and displayed to the user [1].

A fiber under test may have components or phenomena that cause discontinuities in the backscattering signal. These discontinuities are called events and can be divided into two categories: reflective event or non-reflective event.

The reflective events are Fresnel peaks and result of sudden changes in density of the material [2], usually fiber-to-air transitions. The most common examples are mechanical splices and connectors.

The non-reflective events occur due to MFD (modal field diameter) variations caused by geometric changes or differences in the glass fiber [2]. If the loss due to the event is positive, the event is called Step, if it is negative the event is called Gainer. The main cause of non-reflective events in the fiber (without defects) are fusion splices.

One possible illustration of an OTDR trace is shown in Fig. 1.

Fig. 1. Exemplary OTDR trace

The paper is organized as follows: in section 2 techniques for post processing of OTDR data, in section 3 event detection methods, in section 4 the proposed methodology is discussed, in section 5 the results of the proposed methodology and section 6 draws conclusions.

II. POST PROCESSING TECHNIQUES

High optical attenuation results in lower signal to noise ratio (SNR), lower system performance and higher system cost. To reduce the noise level, it may be necessary to increase the amount of averaging, digitally filter the OTDR graph signal or
possibly use methods with signal correlation. Some techniques are discussed in this section.

A. Averaging

One way to improve the SNR is averaging various captures made by the OTDR. Averaging is a time consuming process, the higher the number of averages, the longer it takes to analyze the fiber. The amount of averaging an OTDR can perform with a given amount of time depends on the length of the fiber.

Averaging gives impressive gains in dynamic range but has diminishing returns with the increase of the number of averages made. For example, for 10000 averages there will be an SNR improvement of about 20 dB and for 100000 averages an improvement of about 25 dB.

B. Filtering

Filtering is a technique used to reduce noise and increase the dynamic range. There are various filtering techniques like the finite impulse response (FIR) filters. While filtering is effective in reducing noise in the OTDR trace, it can also introduce errors in the distance measurement when applied improperly, especially in non-reflective events.

C. Decimation

Decimation is another technique used to increase the SNR and consists of two operations: sampling and rate reduction. The sampling process is shown by (1) [3].

\[
y_n = \begin{cases} 
x_n & \text{if } n = kM \\
0 & \text{if } n \neq kM
\end{cases}
\]

(1)

The reduction of rate is to not consider the zero values and consequent adjustment of the underlying temporal interval. In the case of OTDR, increasing the sampling interval can lead to measurement errors.

III. EVENT DETECTION METHODS

There are several different techniques for detection of events which are useful for the data post-processing OTDR data. Some methods are discussed in this section. The accuracy of event detection methods is difficult to ensure when the acquired data presents low SNR.

A. Wavelet Analysis

The method of wavelet analysis is used to find discontinuities in the OTDR trace. The wavelet transform is the correlation of the signal to be analyzed with a wavelet prototype function (mother wavelet). The OTDR trace can be represented in terms of a wavelet expansion using coefficients in a linear combination of the wavelet functions [4], but with less samples than the original signal.

Due to the loss of spatial resolution, it is virtually impossible to precisely locate events for signals with low SNR [5]. This method is also not effective in locating non-reflective events [6].

B. Sliding Window

For the detection problem of non-reflective events immersed in noise it was tested the sliding window method, which consists in using the method of least squares. It is made a best line fit using N samples before and after a certain point. Then, the difference between the y-intercept of both fits is calculated.

The point will be considered the beginning of the non-reflective event if the difference exceeds the threshold imposed for non-reflective events, or else, the window “slides” to the next step and the process starts again.

The accuracy of this method is difficult to ensure in acquired low SNR data.

C. Segmented Regression

The accuracy of the location of non-reflective events can be improved by the segmented regression method, which requires a line fit of the backscattering level before the event and another line fit after the end of the event. It also calculates a line fit in the event area.

Theoretically the intersection of each pair of line fits should provide the beginning and end of the event. In practice, this method only works if after the start of the event the slope is constant in the total duration of the event. If the slope changes, the end result will not be accurate.

D. Template Matching

Another method that can be used is template matching. With prior knowledge of the signal trace in the event area, you can build an event model according to their geometric property [5]. This method consists in moving the model and computing the normalized cross-correlation between the model and the signal section, which is defined in (2) [5].

\[
\rho(k) = \frac{\sum_{i=0}^{n} f_i \cdot t_i}{\sqrt{\sum_{i=0}^{n} f_i^2 \cdot \sum_{i=0}^{n} t_i^2}}
\]

(2)

Template matching works well locally, but it’s not a good option for detecting the event areas throughout the signal [5].

This method has the same limitations of the segmented regression if a composite of three line segments is used as a model. If there is prior knowledge of the geometry of the event, it is possible to obtain better results.

IV. EVENT DETECTION ALGORITHM

Based on the studied methods, it was implemented an event detection algorithm. The Kalman filter was chosen for signals with few samples and match filter for signals with many samples.
The algorithm requires the insertion of the following parameters:

- Refractive index
- Upper threshold to avoid the initial deadzone
- Lower threshold to avoid the initial deadzone
- Threshold for non-reflective event detection in the estimated attenuation factor (only used in Kalman filter)
- Threshold forreflerevent detection in the backscatter signal (only used in Kalman filter)
- Gamma (only used in Kalman filter)

After inserting the initial parameters, the analysis of the fiber is automatic.

A. Match Filter

The match filter method consists in the cross correlation of the attenuation factor of the backscatter signal, with a model of the pulse used by the OTDR in the measurement, which is defined in (3).

\[ C(k) = \sum_{i=0}^{n} (-\alpha_i + k) M_i \]  

Figure 2 shows an example of a result of the correlation for a certain attenuation factor.

With the size of the non-reflective event almost equal to the pulse width, the local maximum of the correlation indicates the beginning of a non-reflective event.

If the non-reflective event is a gainer or step, some corrections are made to the start of the event. This method is also used to locate reflective events since the duration is similar to the pulse width.

Of all the event detection techniques studied in this paper, the match filter is the most noise resistant method and presents great accuracy.

The match filter presents problems if the spatial resolution is reduced. If the size of the model contains fewer samples, the correlation result will be a zoom of the attenuation factor and the local maximum in the correlation result will match the maximum of the attenuation factor and not the start of the event. Because of this reason, it’s required the use of another method for under-sampled signals.

B. Kalman Filter

The Kalman filter is a derivative filter that can be used to calculate the attenuation factor of the fiber, detecting reflective and non-reflective events. In a perfect backscattering signal (no noise), the slope is constant in zones without events. The presence of an event will represent a discontinuity in the attenuation factor as the slope will be changed. The Kalman filter identifies these discontinuities in the attenuation factor, effectively providing information about the events.

To design a discrete time Kalman filter its required to build a linear model of the backscattering signal and the attenuation factor and then calculate the optimal estimator of the attenuation factor. This method is capable of locating minute non-reflective events and reflective events, using an appropriate threshold on the attenuation factor [6]. This method is applicable only while the magnitude of the signal exceeds the noise. The equations used in this method are available in [6].

This method is used to detect small non-reflective events immersed in noise. In the presence of low SNR, the calculated attenuation factor oscillates around the expected value. This oscillation increases with the decrease of SNR. If the oscillation is greater than the attenuation factor caused by the event, the event is undistinguishable, and it becomes impossible to make a threshold detection. By applying the Kalman filter to the signal, we obtain an estimate of the optimal attenuation factor in where it is possible to discern the event immersed in noise. Fig. 3 shows an example of the attenuation factor of the backscattering signal in red and the optimal estimation of the attenuation factor in blue.

By applying a detection threshold, it is possible to detect the non-reflective events present in the signal and avoid false events. The reflective events are detected using a peak detection algorithm in the backscattering signal.

After some intermediate steps, the event table is displayed to the user.
V. EXPERIMENTAL RESULTS

In this section the experimental results are discussed which were gathered by employing the proposed event detection algorithm to the commercial OTDR data from two different fibers under test. The trace of the first example is given in Fig. 4.

![Fig. 4. Trace of example 1](image)

The result of the match filter (excluding the last event) applied to the trace of example 1 is shown in Fig. 5.

![Fig. 5. Result of the match filter for example 1](image)

The trace plot and the estimated attenuation factor of the kalman filter (in the area with non-reflective events) of example 2 are shown in Fig. 5 and Fig. 6 respectively.

![Fig. 6. Trace of example 2](image)

![Fig. 7. Result of the match filter for example 2](image)

Results are compared in terms of distance with the values from the commercial OTDR used in the measurements of the fibers. Table I and Table II summarize the experimental results showing that the algorithm is highly accurate and noise resistant. The “Event Type” can be:

- Reflective (R)
- Non-Reflective (NR)
- False (F)

<table>
<thead>
<tr>
<th>Example Nº</th>
<th>OTDR Event Position (km)</th>
<th>Calculated Event Position (km)</th>
<th>Event Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.3007</td>
<td>25.2824</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>35.3990</td>
<td>35.3807</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>50.4367</td>
<td>50.4550</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>75.5910</td>
<td>75.5727</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>100.8551</td>
<td>100.8642</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>126.6863</td>
<td>125.9911</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td>161.0608</td>
<td>-</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>166.0185</td>
<td>-</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>171.7445</td>
<td>176.2906</td>
<td>R</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Example Nº</th>
<th>OTDR Event Position (km)</th>
<th>Calculated Event Position (km)</th>
<th>Event Type</th>
</tr>
</thead>
<tbody>
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<tr>
<td></td>
<td>-</td>
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<td>-</td>
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<td>16.8645</td>
<td>16.8679</td>
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<td></td>
<td>31.3477</td>
<td>31.3511</td>
<td>R</td>
</tr>
</tbody>
</table>
The commercial OTDR showed difficulties in event detection in low SNR by not being able to detect minute events but by also detecting false events. The proposed algorithm presents better results than the commercial OTDR, having a higher score in event detection capability and accuracy.

VI. CONCLUSION

In this document the OTDR was studied, which allows visualization of events occurring along the fiber. This involved the study and implementation of event detection methods and signal processing techniques in order to detect phenomena occurring in the fiber automatically.

The match filtering method was proven to be very effective in the event detection, even at low SNR. When the number of samples decreases, the accuracy of the results deteriorates. When the detection is made, the location of the reflective events is always correct while the location of the beginning of the non-reflective events have an uncertainty of a few samples. This method doesn’t use threshold detection parameters, which equates to an event detection dependent on signal quality and not the user parameters.

The Kalman filter method was implemented to overcome the inefficiency of the match filtering method in the non-reflective event detection of undersampled signals, being able to make a good detection with the correct initial parameters and with good accuracy. Because of the need to insert initial parameters, this method becomes less preferable that the match filter, as it relies heavily on user-entered parameters.

The proposed algorithm provides an effective solution for event detection in OTDR.

REFERENCES